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Evaluation of Flexural Rigidity of Composite Boards

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Abstract

The flexural rigidity of composite boards with various constitution along the thickness were investigated as a part of a continuing effort to evaluate the bending stiffness of boards efficiently. The equation with integral calculus was proposed to determine the equivalent bending moduli of elasticity (MOE) of composite boards based on the flexural properties of their individual components. In order to test the reliability of the predicted results, applicability of the method derived in this study was verified by using previous experimental results. Two different groups of composite boards were selected. One is that their density is distributed continuously along the thickness, such as particleboards with U-shaped density profiles. Another is those with density distributed discontinuously along the thickness. The typical boards which were made from different lignocellulostic materials, wood fiberboard with oriented bamboo strand face and bagasse particleboard with oriented bagasse strand face were taken as the objects. Consequently, it could be concluded that the availability of this equation depends on the constituent properties significantly. For the bamboo-reinforced fiberboards, it is inapplicable due to the fact that the reinforced material is too different from the base material so that the behavior of the phase interface could not be ignored. However, for the unreinforced particleboards or bagasse composite boards, the calculated values agreed with the data resulting from the experimental measurement quantitatively. It indicates that the equation proposed in this study is only applicable in judging the mechanical properties of composite boards with properties distributed gradually along the thickness.

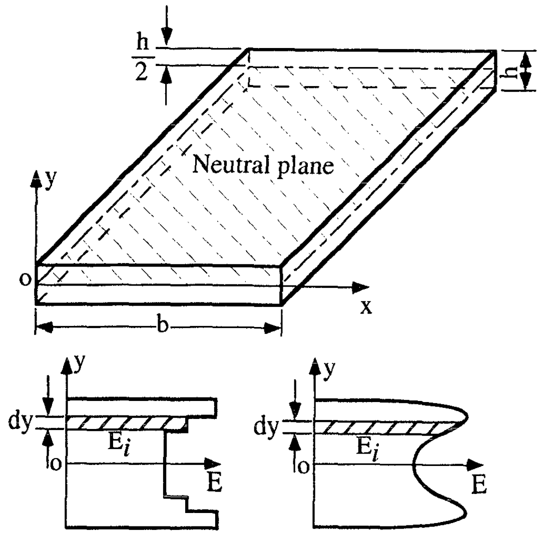
Key words: composite board, structural panels, flexural rigidity, modulus of elasticity, FEM.

Introduction

The structural panel applications require products to be stiff and strong in bending. This entails a resistance to the horizontal compression and tension forces caused by applied moments. There are differential strength requirements through the thickness of the panel, such that the stress intensity decreases linearly from the surface to the center of the thickness -it is usual in the neutral axis, since almost all of the composite boards have symmetrical constitution in their thickness. As the orthotropic mechanical properties of wood stipulate a longitudinal orientation of wood product elements, especially in the face of the products, to attain maximum stress resistance in bending. In order to display the maximum superiority of flexural stiffness of composite boards, a lot of new products have been developed for structural applications. One kind is the composites from both woody and nonwoody, such as metal-reinforced wood composite[1], glass or graphite fiber-reinforced wood-based composites[2~3], bamboo-reinforced wood fiberboards[4] and bagasse-reinforced particleboards[5], etc. Another is only composed of wood elements, but with different density distribution along its thickness.

Our two successful attempts have been done to estimate the moduli of elasticity (MOE) of composite boards by computer simulation using finite element method (FEM). One is for three-layered (sandwich) composite boards made from different lignocellulostic materials, including the wood fiberboards reinforced by aligned bamboo strand face[4], and the bagasse particleboards reinforced by aligned bagasse strand face[5]. Another is the wood particleboard with various density profile along the thickness[6]. All of the calculated results showed agreement with the experimental results measured through traditional static testing.

However, FEM computation is simple for the former case with clear lay-up structure, but it entailed great expense due to the finer element dividing, and material property definition for the analytical model of the latter case. This study is a trial to find an easier way to evaluate the bending moduli of elasticity corresponding to the certain constitution along the thickness. The differential bending resistance from each component through the thickness of the whole board was focused on, so as to estimate its effective flexural stiffness. Both of the three-layered composite boards and particleboards with different density profiles were chosen as the objects.



a. Discontinuous distribution of E   b. Continuous distribution of E

Fig.1 Composite panels with different constitution along the thickness
Note: E_i: Elastic modulus of the ith component

Theory

Based on the transformed section theory of composite materials, the effective flexural stiffness of composite board could be represented as Equation (1). It depends on constituent components (refer to Fig.1), such as their mechanical properties, ratios and geometrical positions in overall composite.

$$MOE = \frac{1}{I}\int_{A_i} E_i \cdot I_i = \frac{1}{I}\int_{A_i} E_i \cdot y_i^2 \cdot dA_i = \frac{2}{I}\int_0^{\frac{h}{2}} E_i \cdot y_i^2 \cdot b \cdot dy \qquad (1)$$

where:
MOE : elastic modulus of overall composite board in bending
E_i : elastic modulus of the ith component
I : moment of inertia for overall composite board to the neutral plane
I_i : moment of inertia for the ith component to the neutral plane
dA_i : cross-sectional area for the ith component
y_i : distance between the center of the ith component and the neutral plane of overall composite

dy: thickness of the *i*th component

b: width of composite board

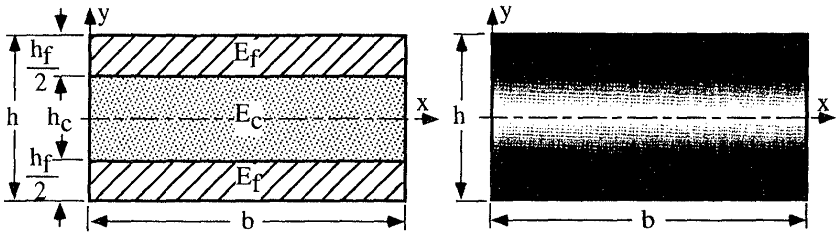
h: thickness of overall composite board

This equation is based on some assumptions regarding material behavior and composite geometry, including perfect adhesion at the phase interface, linear elastic material behavior, absence of residual stress, and ignoring the contribution of glue.

For optional three-layered (sandwich) composite material with rectangular cross sections (Fig.2), Equation (1) can be rewritten as

$$\mathrm{MOE} = E_f - \left(\frac{h_c}{h}\right)^3 (E_f - E_c) \qquad (2)$$

the subscript letters of f and c denote the face and the core materials.



a. Lignocellulostic board with three-layered constitution

Face: $E = E_f$, $\left|\frac{h_c}{2}\right| \leqq y \leqq \left|\frac{h}{2}\right|$

Core: $E = E_c$, $0 \leqq y < \left|\frac{h_c}{2}\right|$

b. Wood particleboard with multi-layered constitution

$E = f(y)$

Fig.2 Cross-sectional view of composite boards

Note: The subscript letters of f and c denote the face and core materials, E : Modulus of elasticity

Verification by previous samples

To ascertain the reliability of calculating the MOE of composite boards with varied constitution, the composite boards in our previous experiments were quoted as the calculating objects.

Fig.2 shows their cross-sectional views. One is the three-layered composite boards using different lignocellulostic materials[4~5]. Another is wood particleboard with various density distribution along the thickness[6].

Table 1 gives the constitution and mechanical properties of three-layered composite boards. Bamboo-wood composite boards and bagasse composite boards were defined, respectively. The former were constructed with aligned bamboo (*Phyllostachys pubescens* Mazel) strand in the face layers and lauan (*Shorea* spp.) wood fiber in the core, and the latter were composed of aligned bagasse strand face and bagasse particle core. All of the boards were produced using an

Table 1. Constitution and mechanical properties of three-layered composite boards

Type of composite boards	Materials		Face and core ratios	Modulus of elasticity (10^3 kgf/cm^2)	
	Face	Core	$h_f : h_c$	Face	Core
Bamboo-wood boards	Bamboo strand	Wood fiber	1 : 3 1 : 1 3 : 1	95	21
Bagasse boards	Bagasse strand	Bagasse particle	1 : 3 1 : 1	33	29

isocynate resin. Their elastic moduli were measured by destructive static bending test. The relationship between constituent ratio (the weight ratio of face and core materials) and the moduli of elasticity (MOE) of these three-layered composite boards was also clarified by the numerical analysis using the finite element method.

Fig.3 exhibits the density profiles of four conventional wood particleboards produced from lauan (*Shorea* spp.) particles and an isocynate resin. Their density distribution were measured by Density-Profile Scanner (Raytest Isotopenmeβgeräte Gmbh). Their mean density (ρ) were 0.52, 0.54, 0.71 and 0.74 g/cm^3, respectively. However, these conventional particleboards could be considered to consist of thin layers of homo-profile boards (board with flat density profile) with various mean density. In this regard, the moduli of elasticity along the board

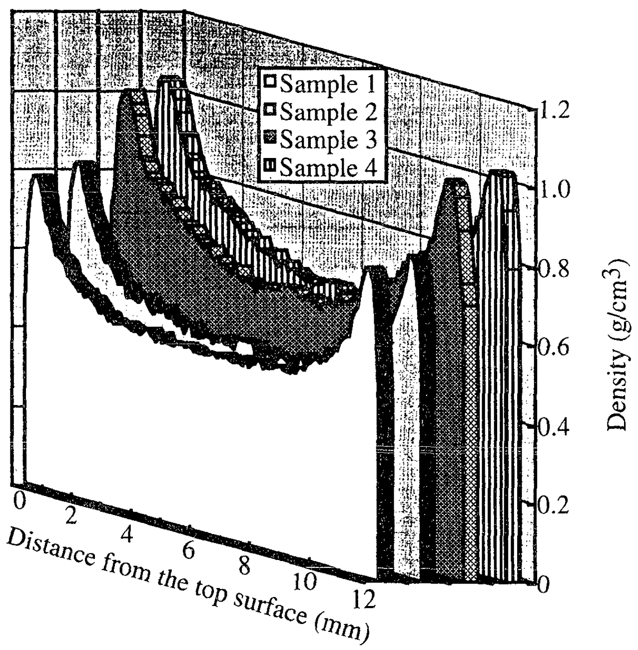


Fig.3 Density profiles of wood particleboards

thickness could be determined from the following equation, based on the relationship between the mean density and the basic properties of homo-profile particleboards.

$$E = -21.0 + 41.0\rho + 35.0\rho^2 (\mathrm{kgf/cm^2}) \quad (3)$$

Results and discussion

The MOE of two kinds of composite boards were calculated and compared with the experimental data. The incorporation of shear effect corrections were conducted only in calculating the MOE from the deflection using finite element method.

Table 2. Comparison of MOE of three-layered composite boards amongst experimental, FEM calculating and integral calculus

Type of composite boards	Materials		Face and core ratios	Modulus of elasticity (10^3 kgf/cm^2) Difference from exp. value		
	Face	Core	$h_f : h_c$	Exp.	FEM	Eq.(2)
Bamboo-wood boards	Bamboo strand	Wood fiber	1 : 3	54.5	62.6 (+14.9%)	63.8 (+17.1%)
			1 : 1	71.2	82.7 (+16.2%)	85.8 (20.5%)
			3 : 1	81.0	89.0 (+9.9%)	93.8 (+15.8%)
Bagasse boards	Bagasse strand	Bagasse particle	1 : 3	39.1	43.1 (+10.2%)	39.5 (+1.0%)
			1 : 1	46.0	50.0 (+8.7%)	47.1 (+2.2%)

Table 2 shows the comparison of modulus of elasticity (MOE) values for the three-layered composite boards obtained from experiment, Equation (2), and finite element method calculating. The following observations can be drawn from this table.

1. The moduli of elasticity of both wood fiberboards reinforced by aligned bamboo strand face, and the bagasse particleboards reinforced by aligned bagasse strand face increased incrementally in face and core ratios. This was due to the oriented bamboo or bagasse strand in the face of the boards that could attain maximum stress resistance in bending. Improvements ranged from 2.5 to 3.9 times greater than the MOE of unreinforced wood fiberboard (core material only), and 1.3 to 1.6 times the unreinforced bagasse particleboards.

2. Compared to bagasse composite boards, bamboo-wood composite boards showed greater improving of MOE in the same face and core ratios, because bamboo strand is much stiffer than bagasse, and it could contribute much more to the face against bending.

3. MOE of bagasse composite boards could be obtained using Equation (2) with good

reliability, with less than 3% difference from the experimental MOE values. However, it will be slightly overestimated by finite element method.

4 . Almost all of the calculated MOE values for the bamboo-wood composite boards are greater than those measured from the static bending test. Especially, the theoretical stiffness based on bending stresses alone appear much larger MOE than those from FEM computation.

From Fig.4, it is clear that increment in mean density results in a proportional increase in MOE. Equation (1) is fairly accurate in determining the MOE of wood particleboards with various density profiles. It is therefore possible to predict the properties of particleboards with imaginary constitution, in other words, it is able to apply in the design stage of particleboard constitution.

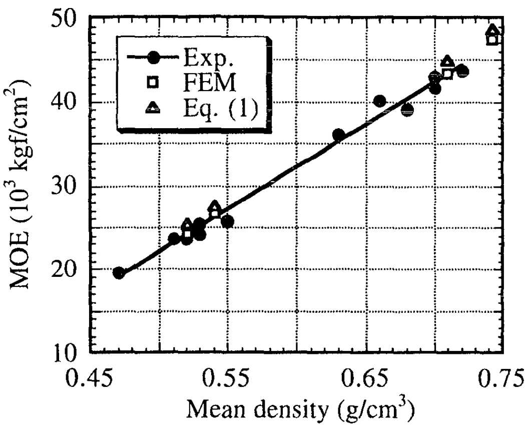


Fig.4 Comparison of MOE values obtained from experimental, FEM computation and Equation (1)

To sum up the above, it is interesting to note that the availability of Equation (1) depends on the constitution of the composite boards, including the difference of component stiffness, the slope gradient of mechanical properties between adjacent materials, etc. To put it concretely, in the case where the mechanical properties of the composite changed gradually, gently and continuously, such as particleboard shown in Fig.3, or the case of bagasse particleboard with steep changing in material properties but a little difference (the ratio is lower than 2) amongst components (Table 1), Equation (1) could be applied enough to evaluate their MOE. However, beyond the above cases, especially, if it is too different in the mechanical properties of components, such as bamboo-wood composite boards with the ratio around 4.5, more empirical data are required to come up with a more reliable estimation equation for the MOE value of the composite boards.

Conclusion

An approach to modeling the composite boards for evaluating their flexual rigidities in this study is conducted. The transformed theory is used for composite materials to describe the net behavior after combining two or more materials together. Compared to the finite element method (FEM), this method allows greater flexibility in modeling due to the relative ease of computation.

In the case where the mechanical properties of composite boards changed gradually, such as unreinforced particleboard and bagasse composite boards, their MOE could be evaluated by Equation (1) efficiently (the differences were within 5%). However, Equation (2) tends to overestimate the MOE values (with differences ranging from 16% to 21%) in the case where the properties of constituent materials changed suddenly, such as bamboo reinforced fiberboards. Because the Equation (1) is based on some assumptions, such as perfect adhesion at the phase interface, linear elastic material behavior, etc. It seems that more empirical data are required to come up with a more reliable estimation equation for the MOE value of the particular composite boards. Consequently, more data is needed to make it easier to adjust the relative volumes and the geometric contribution of constituent materials so that its basic properties satisfy the performance specifications for wood-based composite boards. The results obtained showed that Equation (1) or (2) could be used to determine the modulus of elasticity (MOE) of composites with various constitutions along the thickness.

Therefore, these results will not only be useful to assess the flexural properties of accomplished composite boards, but also can be applied to determine the effective properties based on the constituent components with the imaginary constitution so as to be extended to apply in the design stage of composite constitution to meet the needs of the engineer and structural application.

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